

Auxiliary Field Diffusion Monte Carlo study of the Hyperon-Nucleon interaction in Λ -hypernuclei

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Abstract

We investigate the role of two- and three-body Λ -nucleon forces by computing the ground state of a few Λ -hypernuclei with the Auxiliary Field Diffusion Monte Carlo algorithm. Calculations have been performed for masses up to $A = 41$, including some open-shell hypernuclei. The results show that the use of a bare hyperon-nucleon force fitted on the available scattering data yields a consistent overestimate of the Λ -separation energy B_Λ . The inclusion of a hyperon-nucleon-nucleon interaction systematically reduces B_Λ , leading to a qualitatively good agreement with experimental data over the range of masses investigated.

Keywords: ΛN interaction, Λ -hypernuclei, Λ -separation energy, Auxiliary Field Diffusion Monte Carlo (AFDMC)

1. Introduction

The outer core of a neutron star (NS), where matter is supposed to have a density close to the saturation value, can be safely modeled as a gas of neutrons with a small fraction of protons and leptons (see for example Ref. [1]). At the larger densities reached in the inner core, the composition of matter is instead rather uncertain. The available observations of NS masses of order $2M_\odot$ [2, 3] has greatly reduced the softening of the equation of state (EOS) needed to yield a maximum mass in agreement with observational data. This fact seems to strongly question one of the potential sources of softening, i.e. the onset of heavier hadrons, such as hyperons, for large enough values of the chemical potential of NS matter. Most recent calculations on neutron matter with the inclusion of hyperons give a rather strong softening of the EOS [4–8]. However, results are strictly model dependent. A number of hyperon-nucleon interactions have been used (Nijmegen, Jülich, χ EFT), with no overall agreement in the results. Some other approaches exist, that instead predict very small changes to the neutron star structure once the hyperons are included in the model [9, 10].

The only reliable benchmarks on hyperon-nucleon model forces can be made on the experiments with hypernuclei. Most of the limited available data concern single Λ -hypernuclei. Only a few Λ -nucleon scattering data are available. Binding energies, excitation energies and hyperon-separation energies for approximately 40 Λ -hypernuclei are available (for recent results see e.g. [11–13]). The lack of data reflects in the large arbitrariness in the definition of a hyperon-nucleon potential.

In this paper we focus on a realistic Λ -nucleon potential based on the Argonne-like interaction proposed by Bodmer, Usmani and collaborators ([14, 15] and references therein). The potential is projected in coordinate space including both the ΛN the and ΛNN channel, and a realistic description of the hard-core repulsion between baryons. The final target will be refitting the parameters of the hyperon-nucleon-nucleon force in order to reproduce the experimental data on the Λ -separation energy on a set of selected hypernuclei in a rather wide mass interval.

The Λ separation energy B_Λ , defined as the difference between the binding energy of the nucleus ^{A-1}Z and that of the corresponding hypernucleus $^\Lambda_A\text{Z}$, is here computed by means of the Auxiliary Field Diffusion Monte Carlo (AFDMC) method [16].

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2. Hamiltonians and the Λ -nucleon interaction

We describe nuclei and Λ -hypernuclei as systems made of non-relativistic point-like particles interacting via the following Hamiltonians:

$$H_{nuc} = \sum_{i=1}^{A-1} \frac{p_i^2}{2m_N} + \sum_{i<j}^{A-1} v_{ij}, \quad H_{hyp} = H_{nuc} + \frac{p_\Lambda^2}{2m_\Lambda} + \sum_{i=1}^{A-1} v_{\Lambda i} + \sum_{i<j}^{A-1} v_{\Lambda ij}, \quad (1)$$

where A is the total number of baryons, nucleons plus the Λ particle. In the nucleon Hamiltonian we use the Argonne AV4' and AV6' two body-potentials [17], that are simplified versions of the Argonne AV18 [18]. As a test of the sensitivity of B_Λ on the choice of the NN interaction, we also performed calculations with the Minnesota potential [19]. The Λ -nucleon interaction is here modeled by the two- and three-body potentials developed by Usmani et al. [14, 15]. It is important to note that the cited nuclear potentials do not provide the same accuracy as AV18 in fitting NN scattering data. In addition, three-body NNN forces are purposely disregarded for technical reasons related to the AFDMC algorithm used. We rely on the assumption that when taking the difference between the binding energies of a nucleus and the corresponding Λ -hypernucleus, most of the nucleon interaction energy cancels. We shall see that this assumption is consistent with our results, thereby confirming that the specific choice of the nucleon Hamiltonian should not significantly affect the results on B_Λ .

Effects of the ΛNN force should instead not be neglected in the Hamiltonian. The lowest order in the Λ -nucleon interaction involves the exchange of two pions (TPE), in the two- as well as three-body channel (see Fig. 1). This is due to isospin conservation which allows only $\Lambda\pi\Sigma$ vertex and so forbids the one pion exchange process.

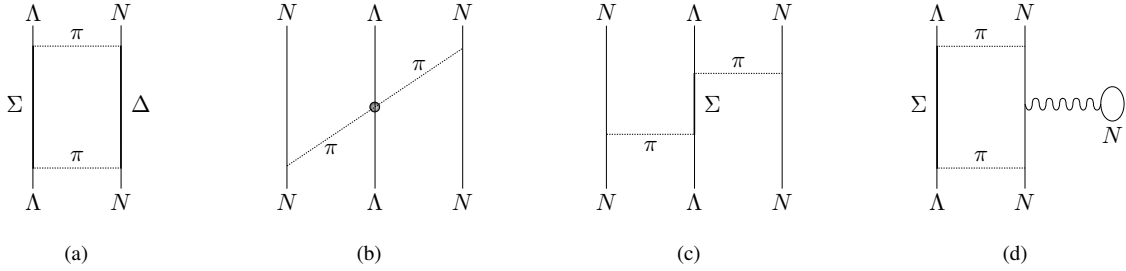


Figure 1: Schematic construction of the Λ -nucleon interaction. 2π exchange processes between nucleons and the Λ particle. 1(a) represents the two-body ΛN channel. 1(b), 1(c) and 1(d) are the three-body ΛNN channels. For more details see Refs. [14, 15].

The ΛN potential is written as a sum of a central term, which also includes a Λ -N exchange accounting for the one kaon exchange process, and a spin-dependent part. The TPE process is modeled with the usual one-pion exchange potential acting twice, as in the Argonne forces. More details can be found in Refs. [14, 15].

The three-body Λ -nucleon interaction takes contributions from the TPE diagrams in the s -wave channel ($v_{\Lambda ij}^S$, Fig. 1(b)) and in the p -wave channel ($v_{\Lambda ij}^P$, Fig. 1(c)). Short range effects are accounted for by a phenomenological central repulsive term $v_{\Lambda ij}^D$:

$$\begin{aligned} v_{\Lambda ij}^S &= C^S Z(m_\pi r_{i\Lambda}) Z(m_\pi r_{j\Lambda}) (\boldsymbol{\sigma}_i \cdot \hat{\mathbf{r}}_{i\Lambda} \boldsymbol{\sigma}_j \cdot \hat{\mathbf{r}}_{j\Lambda}) \boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j, \\ v_{\Lambda ij}^P &= -\left(\frac{C^P}{6}\right) (\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_j) \{X_{i\Lambda}, X_{j\Lambda}\}, \\ v_{\Lambda ij}^D &= W^D T_\pi^2(m_\pi r_{i\Lambda}) T_\pi^2(m_\pi r_{j\Lambda}) \left[1 + \frac{1}{6} \boldsymbol{\sigma}_\Lambda \cdot (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\right]. \end{aligned} \quad (2)$$

The definition of the functions $Z(x)$ and $X_{i\Lambda}$ as well as the set of parameters of the two-body ΛN and three-body ΛNN interactions can be found in Refs. [14, 15].

We solve the ground-state of the many-body nuclear and hypernuclear Hamiltonians by means of the AFDMC method, originally introduced by Schmidt and Fantoni [16]. By sampling configurations of the system in coordinate-spin-isospin space using Monte Carlo algorithms, we evolve an initial trial wave function Ψ_T in imaginary-time. In the $\tau \rightarrow \infty$ limit, the evolved state approaches the ground-state of H . Expectation values are computed averaging over the sampled configurations, and for large τ , the ground state energy of the system is obtained. For more details see e.g. Refs. [20, 21]. The extension of the AFDMC method to Λ -hypernuclei is technically straightforward.

3. Results and discussion

In Tab. 1 the results for B_Λ in ${}^5_\Lambda\text{He}$ are reported. Results were obtained using different nuclear Hamiltonians. The second column corresponds to calculations using the ΛN interaction only. The numerical results with the AV4' and Minnesota NN potentials are partially consistent. The value obtained with AV6' has a statistically significant deviation. All results for B_Λ are overestimated, being roughly twice the experimental value. The third column refers instead to calculations in which the three-body ΛNN force, with the set of parameters described in Ref. [14], was included. The three-body force significantly reduces the Λ -separation energy, yielding a more realistic value. It is very interesting to notice that the disagreement between calculations performed using different nuclear interactions is also reduced below statistical significance. The same conclusions were obtained by studying the ${}^{17}_\Lambda\text{O}$ hypernucleus, for which the discrepancy between B_Λ computed using different nuclear interactions is few percent. For this reason we are confident that the Λ -separation energy is not too sensitive to the details of the nuclear interaction.

Nuclear potential	B_Λ^{2B}	B_Λ^{2B+3B}	B_Λ^{exp}
Argonne V4'	7.1(1)	5.0(1)	
Argonne V6'	6.3(1)	5.1(1)	3.12(2)
Minnesota	7.4(1)	5.0(1)	

Table 1: Λ -separation energies (in MeV) for ${}^5_\Lambda\text{He}$ obtained using different nuclear potentials. B_Λ^{2B} refers to the Λ -separation obtained with the two-body ΛN interaction only. B_Λ^{2B+3B} is the result for B_Λ when the three-body ΛNN interaction is included. In the last column the experimental value of B_Λ is from Ref. [22].

The Λ -separation energy as a function of $A^{-2/3}$ is shown in Fig. 2. B_Λ is calculated using the two-body ΛN potentials only (upper red curve) and including also the three-body ΛNN interaction (central blue curve). The nuclear potential is the AV4'. Qualitatively similar results were obtained using the AV6' or Minnesota NN forces. The dashed green curve is the guide line following the experimental data. It is evident that the two-body Λ -nucleon interaction alone gives an unrealistic separation energy. The saturation energy, which is estimated to be around 30 MeV, cannot be reproduced. The inclusion of the three-body hyperon-nucleon interaction drastically improves the theoretical prediction in the separation energies, and the extrapolated saturation energy becomes reasonably close to experimental data. We should point out that a fine tuning of the ΛNN parameters might further improve the AFDMC results. In particular, following Ref. [14] the s -wave channel has not been included in the present calculations. Preliminary results on ${}^5_\Lambda\text{He}$ and ${}^{17}_\Lambda\text{O}$ reveal that this contribution is indeed sub-leading, and not scaling with the baryon number. The leading term in the ΛNN potential is the repulsive $v_{\Lambda ij}^D$, which is strictly dependent on A . Calculations for ${}^{17}_\Lambda\text{O}$ performed with different values of W^D , show that it is possible to move the Λ -separation energy closer to the expected result of 13.59 MeV [23], and have a better description of the ${}^5_\Lambda\text{He}$ hypernucleus.

From these results it is clear that the role of the ΛNN force is important in determining the correct Λ separation energy, and should not be neglected. The fact that the leading contribution to the three-body interaction is strictly repulsive in the range of hypernuclei studied, and the fact that it scales with the number of baryons, suggests that the Λ -nucleon potential discussed in this paper, when applied the study of the homogeneous medium, should lead to a stiffer EOS for the Λ -neutron matter. This fact might eventually reconcile the onset of hyperons in the inner core of a NS with the observed masses of order $2 M_\odot$. A study along this direction is in progress.

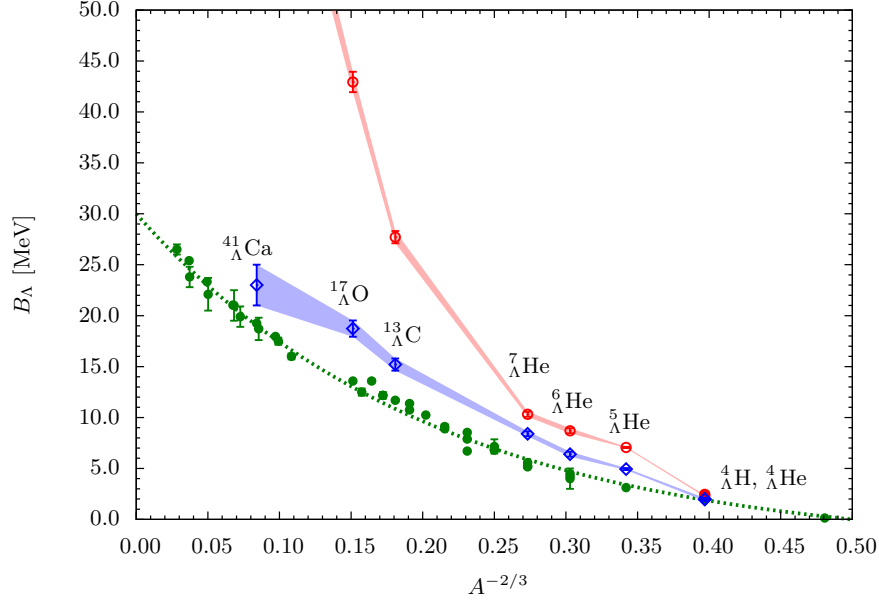


Figure 2: Λ -separation energy as a function of $A^{-2/3}$. Red circles refer to the AFDMC results for the nuclear AV4' potential plus the two-body ΛN interaction. Blue diamonds are the results obtained with the same core nuclear potential but with both the two- and three- body Λ -nucleon forces. Green solid circles refer to the experimental values.

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